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# Search for $B \to \pi \ell^+ \ell^-$ Decays at Belle

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## Abstract

We present a search for the decays $B^+ \to \pi^+\ell^+\ell^-$ and $B^0 \to \pi^0\ell^+\ell^-$, where $\ell^+\ell^-$ is either a $\mu^+\mu^-$ or $e^+e^-$ pair, with a data sample of 657 million $B\overline{B}$ pairs collected with the Belle detector at the KEKB $e^+e^-$ collider. Signal events are reconstructed from a charged or a neutral pion candidate and a pair of oppositely charged electrons or muons. No significant signal is observed and we set an upper limit on the isospin-averaged branching fraction $\mathcal{B}(B \to \pi\ell^+\ell^-) < 6.2 \times 10^{-8}$ at the 90% confidence level.

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In the Standard Model (SM), the decays $B \to \pi\ell^+\ell^-$ are forbidden at tree level and only proceed through flavor-changing neutral currents (FCNC). The possible lowest-order $b \to d\ell^+\ell^-$ processes are either a $Z/\gamma$ penguin or a box diagram, as shown in Fig. 1. FCNC $b \to (s,d)\ell^+\ell^-$ decays can provide stringent tests of the SM in the flavor physics sector. For example, in the future it may be possible to measure the dilepton invariant mass spectrum and the forward-backward asymmetry in the center-of-mass system of the lepton pair, which can provide information on the coefficients of new operators associated with theoretical models [1]. Most of the experimental studies and theoretical predictions are focused on $b \to s\ell^+\ell^-$ decays [2, 3]; however, signatures due to new physics may be observed in $b \to d\ell^+\ell^-$ decays even if no such signature is found in $b \to s\ell^+\ell^-$.

The process $b \to d\ell^+\ell^-$ is suppressed by a factor of $|V_{td}/V_{ts}|^2 \approx 0.04$ relative to $b \to s\ell^+\ell^-$, where $V_{td}$ and $V_{ts}$ are the elements of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [4]. The corresponding branching fraction of the exclusive $B^+ \to \pi^+\ell^+\ell^-$ mode is expected to be $3.3 \times 10^{-8}$, which agrees with the simple power counting expectation [5]. Assuming isospin symmetry,

the branching fraction for $B^0 \to \pi^0\ell^+\ell^-$ is smaller by another factor of $1/2 \times \tau_{B^0}/\tau_{B^+}$ for these decays, where $\tau_{B^0}$ and $\tau_{B^+}$ are the neutral and charged $B$-meson lifetimes, respectively. Thus for SM branching fractions, only a few signal candidates are expected in our data sample.

In this paper, we perform a search for the $B^+ \to \pi^+\ell^+\ell^-$ and $B^0 \to \pi^0\ell^+\ell^-$ decays, where $\ell^+\ell^-$ stands for a $\mu^+\mu^-$ or $e^+e^-$ pair. A data sample of 657 million $B\overline{B}$ pairs collected with the Belle detector at the KEKB $e^+e^-$ collider is examined. Charge-conjugate decays are implied throughout this paper.

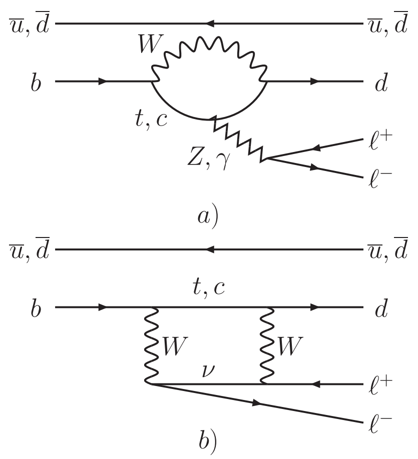


FIG. 1: The quark-level diagrams for $B \to \pi\ell^+\ell^-$ decays.

The Belle detector is a large-solid-angle magnetic spectrometer located at the KEKB collider [6], and consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid that provides a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect $K_L^0$ mesons and to identify muons (KLM). The detector is described in detail elsewhere [7].

We consider all tracks that have a maximum distance to the interaction point (IP) of 5 cm in the beam direction ($z$) and of 0.5 cm in the transverse plane ($r$–$\phi$). We select $\pi^\pm$ candidates from charged tracks having a kaon likelihood ratio less than 0.4; the kaon likelihood ratio is defined by $\mathcal{R}_K \equiv \mathcal{L}_K/(\mathcal{L}_K+\mathcal{L}_\pi)$, where $\mathcal{L}_K$ ($\mathcal{L}_\pi$) denotes a likelihood that combines measurements from the ACC, the TOF, and $dE/dx$ from the CDC for the $K^\pm$ ($\pi^\pm$) tracks. The selection efficiency is about 89% for pions while it removes 91% of kaons. In addition to the information included in the kaon likelihood ratio, muon (electron) candidates are required to be associated with KLM detector hits (ECL calorimeter showers). We define the likelihood ratio $\mathcal{R}_x$ ($x$ denotes $\mu$ or $e$) as $\mathcal{R}_x \equiv \mathcal{L}_x/(\mathcal{L}_x + \mathcal{L}_{not-x})$, where $\mathcal{L}_x$ and $\mathcal{L}_{not-x}$ are the likelihood measurements from the relevant detectors [8]. We select $\mu^\pm$ candidates with $\mathcal{R}_\mu > 0.9$ if the momentum of $\mu^\pm$ is greater than 1 GeV/$c$; for the $\mu^\pm$ candidates with lower momentum (0.7–1.0 GeV/$c$), $\mathcal{R}_\mu$ is required to be greater than 0.97. These requirements retain about 80% of muons while removing 98.5% of pions. Candidates for $e^\pm$ are required to have a minimum momentum of 0.4 GeV/$c$, $\mathcal{R}_e > 0.9$, and $\mathcal{R}_\mu < 0.8$. These requirements keep about 90% of electrons while they remove 99.7% of pions. Bremsstrahlung photons emitted by the electrons are recovered by adding neutral clusters found within a 50 mrad cone along the electron direction. The energy of the additional photon is required to be less than 0.5 GeV. For $\pi^0 \to \gamma\gamma$ candidates, a minimum photon energy of 50 MeV is required and the invariant mass must be in the range 115 MeV/$c^2 < M(\gamma\gamma) <$ 152 MeV/$c^2$, corresponding to $\pm$ 3 $\sigma$ for the $\pi^0$ reconstruction. Requirements on the photon energy asymmetry, $|E_\gamma^1 - E_\gamma^2|/(E_\gamma^1 + E_\gamma^2) < 0.9$, and the minimum momentum of the $\pi^0$ candidate, $p_{\pi^0} >$ 200 MeV/$c$, are introduced to suppress the combinatorial background.

$B$-meson candidates are reconstructed in one of the following modes: $B^+ \to \pi^+e^+e^-$,

$B^+ \to \pi^+\mu^+\mu^-$, $B^0 \to \pi^0 e^+e^-$, or $B^0 \to \pi^0\mu^+\mu^-$. Signal candidates are selected using the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{E_{\rm beam}^2 - p_B^2}$ and the energy difference $\Delta E \equiv E_B - E_{\rm beam}$, where $E_B$ and $p_B$ are the reconstructed energy and momentum of the $B$ candidate in the $\Upsilon(4S)$ center-of-mass (CM) frame, and $E_{\rm beam}$ is the beam energy in this frame. We require $B$-meson candidates to be within the region $M_{\rm bc} > 5.20$ GeV/$c^2$ and $-0.1$ GeV $< \Delta E < 0.3$ GeV ($-0.15$ GeV $< \Delta E < 0.3$ GeV) for the $B^+ \to \pi^+\ell^+\ell^-$ ($B^0 \to \pi^0\ell^+\ell^-$) decays. The signal region is defined by $5.27$ GeV/$c^2 < M_{\rm bc} < 5.29$ GeV/$c^2$, $-0.035$ ($-0.08$) GeV $< \Delta E < 0.035$ GeV for the $\pi^+\mu^+\mu^-$ ($\pi^0\mu^+\mu^-$) mode, and $-0.055$ ($-0.1$) GeV $< \Delta E < 0.035$ GeV for the $\pi^+e^+e^-$ ($\pi^0e^+e^-$) mode. The lower $\Delta E$ bound for the candidate region is designed to exclude possible contamination from similar $B$ decays, e.g. $B \to K^*\ell\ell$, while the wider region in $\Delta E$ for $B^0 \to \pi^0\ell^+\ell^-$ decays is chosen to include the long tail of the signal.

The dominant source of background is continuum $e^+e^- \to q\overline{q}$ events ($q = u, d, c, s$). A Fisher discriminant including 16 modified Fox-Wolfram moments [9] is used to exploit the differences between the event shapes for continuum $q\overline{q}$ production (jet-like) and for $B$ decay (spherical) in the $e^+e^-$ rest frame. We combine 1) the Fisher discriminant, 2) the angle between the momentum vector of reconstructed $B$ candidate and beam direction ($\cos\theta_B$), and 3) the distance in the $z$ direction between the candidate $B$ vertex and a vertex position formed by the charged tracks that are not associated with the candidate $B$-meson into a single likelihood ratio $\mathcal{R} = \mathcal{L}_s/(\mathcal{L}_s + \mathcal{L}_{q\overline{q}})$, where $\mathcal{L}_s$ ($\mathcal{L}_{q\overline{q}}$) denotes the signal (continuum) likelihood. The background from $B \to \ell\nu X$ decays is also found to be large. An additional likelihood ratio $\mathcal{R}_B = \mathcal{L}_s/(\mathcal{L}_s + \mathcal{L}_{B\overline{B}})$ including $\cos\theta_B$ and the overall missing energy is introduced, where $\mathcal{L}_{B\overline{B}}$ is the likelihood for $B\overline{B}$ events.

Continuum background suppression is improved by including $B$-flavor tagging information [10], which is parameterized by a discrete variable $q_{\rm tag}$ indicating the flavor of the tagging $B$-meson candidate and a quality parameter $r$ (ranging from 0 for no flavor information to 1 for unambiguous flavor assignment). Selection criteria for $\mathcal{R}$ and $\mathcal{R}_B$ are determined by maximizing the value of $S/\sqrt{S+B}$, where $S$ and $B$ denote the expected yields of signal and background events in the signal region, respectively, in different $q_{\rm rec}\cdot q_{\rm tag}\cdot r$ regions, where $q_{\rm rec}$ is the charge of reconstructed $B$ candidate. Events with $q_{\rm rec}\cdot q_{\rm tag}\cdot r$ close to $-1$ are considered to be well-tagged and are unlikely to be from continuum processes. For neutral $B$-meson decays, only the dependence on $r$ is considered.

The decays $B \to J/\psi X$ and $\psi' X$ are the dominant peaking backgrounds in the $\Delta E$–$M_{\rm bc}$ candidate region. Events in the regions

$$-0.10 < [M(\mu^+\mu^-) - m(J/\psi,\psi')] < 0.08 \ ,$$
$$-0.20 < [M(e^+e^-) - m(J/\psi,\psi')] < 0.07 \ ,$$

$$0.86\cdot[M(\mu^+\mu^-) - m(J/\psi,\psi') - 0.08] < \Delta E/c^2 < 0.86\cdot[M(\mu^+\mu^-) - m(J/\psi,\psi') + 0.10] \ ,$$
$$0.94\cdot[M(e^+e^-) - m(J/\psi,\psi') - 0.07] < \Delta E/c^2 < 0.94\cdot[M(e^+e^-) - m(J/\psi,\psi') + 0.20] \ .$$

in the $\Delta E$–$M_{\ell^+\ell^-}$ plane are rejected (the limits on the regions are given in units of GeV/$c^2$, see Fig. 2). The decay $B^+ \to J/\psi(\psi')h^+$ ($h^+ = K^+, \pi^+$) can also contribute to the $B^+ \to \pi^+\mu^+\mu^-$ sample. If a muon from $J/\psi(\psi')$ is misidentified as a pion and another non-muon track is at the same time misidentified as a muon, such a background event cannot be removed by the criteria described above. Thus, in addition, events with $-0.10$ GeV/$c^2 < M(\mu\pi) - m(J/\psi,\psi') < 0.08$ GeV/$c^2$ are removed from the $B^+ \to \pi^+\mu^+\mu^-$ sample. An event reconstructed as a $B^+ \to \overline{D}^0(\to \pi^+\pi^-)\pi^+$ or $B^0 \to D^-(\to \pi^0\pi^-)\pi^+$ decay can contribute to the $B \to \pi\mu^+\mu^-$ sample if both pions are misidentified as muons. We reject these events by requiring $|M(\pi\mu) - m(D)| > 0.02$

GeV/$c^2$. The invariant mass of the electron pair is also required to be greater than 0.14 GeV/$c^2$ in order to remove background from photon conversions and from $\pi^0 \to \gamma e^+e^-$ decays. The background contributions from $B \to J/\psi(\psi')X$ and other $b \to c$ decays are estimated using large Monte Carlo (MC) samples. Background from charmless three-body $B$ decays, such as $B^+ \to \pi^+\pi^-\pi^+$ and $B^0 \to \pi^0\pi^-\pi^+$ is estimated using the measured data, taking into account the probabilities of the pions being misidentified as muons. The results are consistent with MC simulations. The background yield from misidentified $B^+ \to K^+\ell^+\ell^-$ decays is calculated from the yield of a dedicated $B^+ \to K^+\ell^+\ell^-$ analysis with a similar analysis procedure, which is then scaled by the kaon to pion misidentification rate.

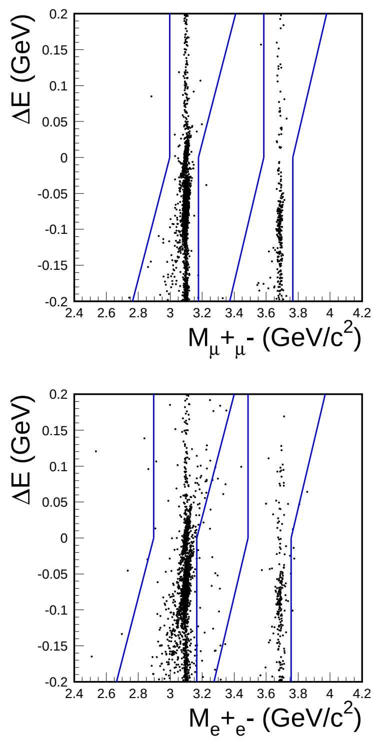


FIG. 2: $\Delta E$ vs. $M_{\ell^+\ell^-}$ distribution of $B \to J/\psi X$ and $\psi' X$ MC events feeding into $\pi^+\mu^+\mu^-$ (left) and $\pi^+e^+e^-$ (right) modes, respectively.

If there are multiple candidates in an event, the candidate with the smallest vertex fit $\chi^2$ is chosen for the $B^+ \to \pi^+\ell^+\ell^-$ modes, and the one with the best $\mathcal{R}$ value is selected for the $B^0 \to \pi^0\ell^+\ell^-$ modes. The fraction of such events are about 11%–13% and 16%–20% for $B^+ \to \pi^+\ell^+\ell^-$ and $B^0 \to \pi^0\ell^+\ell^-$, respectively, according to a MC study.

We perform a simultaneous extended unbinned maximum likelihood fit to $\Delta E$ and $M_{\rm bc}$ with the following likelihood function:

$$\mathcal{L} = \frac{e^{-(N_s+N_{q\overline{q}}+N_{c\overline{c}X}+N_{K\ell\ell}+N_{h\pi\pi})}}{N!} \times \prod_{i=1}^{N} [N_s P_s^i + N_{q\overline{q}} P_{q\overline{q}}^i + N_{B\overline{B}} P_{B\overline{B}}^i + N_{c\overline{c}X} P_{c\overline{c}X}^i + N_{K\ell\ell} P_{K\ell\ell}^i + N_{h\pi\pi} P_{h\pi\pi}^i] \; .$$

where $N$ denotes the number of observed events in the candidate region, and $N_s$ ($P_s^i$), $N_{q\overline{q}}$ ($P_{q\overline{q}}^i$), $N_{B\overline{B}}$ ($P_{B\overline{B}}^i$), $N_{c\overline{c}X}$ ($P_{c\overline{c}X}^i$), $N_{K\ell\ell}$ ($P_{K\ell\ell}^i$), and $N_{h\pi\pi}$ ($P_{h\pi\pi}^i$) denote the event yields (the probability density functions, PDFs, for the i-th event) for signal, continuum, $b \to c$ decays, $B \to J/\psi(\psi')X$, background contributions from $B \to K\ell^+\ell^-$ and $B \to h\pi^+\pi^-$ decays. Since contributions from $B \to J/\psi(\psi')X$ and $B \to K\ell^+\ell^-$ processes are found to be negligible for $B^0 \to \pi^0\ell^+\ell^-$ decays, the associated PDFs are excluded from the fits. The signal PDFs for $B^+ \to \pi^+\ell^+\ell^-$ are assumed to be Gaussian in both $\Delta E$ and $M_{\rm bc}$. The means and widths are verified using $B \to J/\psi K$ decays. Additional Gaussian functions are used to model the tails in the $\Delta E$ distributions. For the $B^0 \to \pi^0\ell^+\ell^-$ modes, the signal PDF is modeled by a two-dimensional smoothed histogram function, including the dependence on $M(\ell^+\ell^-)$. The continuum PDFs for $M_{\rm bc}$ and $\Delta E$ are represented by an empirical background function introduced by ARGUS [11] and a second-order polynomial, respectively. The PDF for $B \to J/\psi(\psi')X$ decays consists of a peaking part and a non-peaking part. The peaking PDF is modeled by Gaussian functions in $\Delta E$ and $M_{\rm bc}$. The non-peaking part, as well as the PDF for other

$b \to c$ decays, is described by the same PDF formulae used for continuum events, but with different parameter values. The distributions of $\Delta E$ and $M_{\rm bc}$ for the $B \to K\ell^+\ell^-$ and $B \to h\pi^+\pi^-$ contributions to the $B^+ \to \pi^+\ell^+\ell^-$ modes are found to be peaking and modeled by Gaussian functions. Due to a much larger tail on $\Delta E$ for the $B^0 \to \pi^0\ell^+\ell^-$ decays, the $B \to h\pi^+\pi^-$ contributions to $B^0 \to \pi^0\ell^+\ell^-$ are modeled by smoothed histogram functions.

Yields for signal and continuum, and the continuum PDF parameters are allowed to float in the fit while the yields and parameters for other components are fixed. The observed signal yields and branching fractions ($\mathcal{B}$) are summarized in Table I. The significance is defined as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\rm max})}$, where $\mathcal{L}_0$ is the likelihood with signal yield constrained to be zero, and $\mathcal{L}_{\rm max}$ is the maximum likelihood. The distributions of $\Delta E$ and $M_{\rm bc}$ with fit results superimposed are shown in Fig. 3.

Systematic uncertainties are summarized in Table II. The dominant systematic uncertainties for the $B^+ \to \pi^+\ell^+\ell^-$ modes stem from electron (4.4%) and muon (5.5%) identification efficiencies, uncertainties of MC decay models (2.6%–3.8%), and tracking efficiencies (3%). The signal MC samples are generated based on the decay model derived from [12], and the uncertainties are evaluated by comparing the MC and data yields for $B^+ \to K^+\ell^+\ell^-$ as a function of dilepton invariant mass. Other uncertainties such as background suppression, which is studied using $B \to J/\psi K$ decays, and PDF modeling are all small. For the $B^0 \to \pi^0\ell^+\ell^-$ modes, the dominant uncertainties are from lepton identifications, PDF modeling (5.3%), $\pi^0$ reconstruction efficiency (4%), and MC models. Other systematic uncertainties are found to be small. There are also some small additive uncertainties that are not proportional to the signal branching fractions. An example is the uncertainty in the background level, which is estimated to be about 0.3-0.8 events. In addition, a fitting bias is found in the MC simulation when signal yields are small (fewer than 2 events). Thus, we quote an additional uncertainty of 0.5 events for each mode.

As no statistically significant excess of signal events is observed, we calculate upper limits of the branching fractions by integrating the likelihood function up to the 90% confidence level. We find,

$$\begin{aligned} \mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) &< 6.9 \times 10^{-8} , \\ \mathcal{B}(B^+ \to \pi^+e^+e^-) &< 8.0 \times 10^{-8} , \\ \mathcal{B}(B^0 \to \pi^0\mu^+\mu^-) &< 18.4 \times 10^{-8} , \\ \mathcal{B}(B^0 \to \pi^0e^+e^-) &< 22.7 \times 10^{-8} . \end{aligned} \quad (1)$$

Systematic uncertainties are included by convoluting the likelihood function with a Gaussian function. The lepton-flavor combined limits are given by

$$\begin{aligned} \mathcal{B}(B^+ \to \pi^+\ell^+\ell^-) &< 4.9 \times 10^{-8} , \\ \mathcal{B}(B^0 \to \pi^0\ell^+\ell^-) &< 15.4 \times 10^{-8} . \end{aligned} \quad (2)$$

Assuming isospin symmetry, the average limit for $B \to \pi\ell^+\ell^-$ is

$$\mathcal{B}(B^+ \to \pi^+\ell^+\ell^-) < 6.2 \times 10^{-8} .$$

In conclusion, the upper limit on the isospin-averaged branching fraction is about twice the SM expectation, and two thirds of the BaBar measurement [13]. A much larger data set, such as will be available from the proposed super $B$ factory [14], is needed to observe this decay mode if the branching fraction is at the level predicted by the SM.

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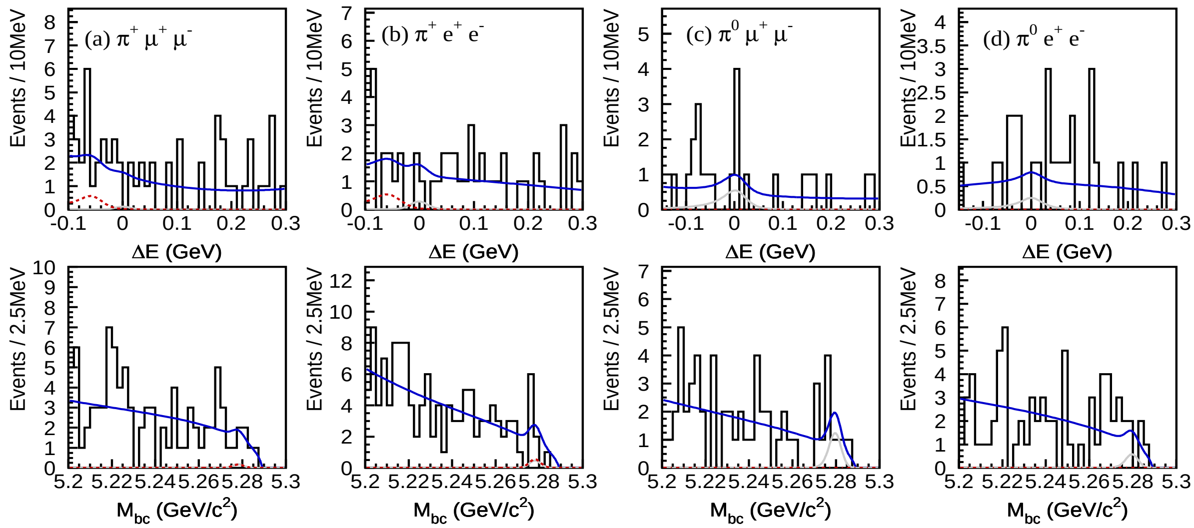


FIG. 3: Distributions of $\Delta E$ ($M_{\rm bc}$) with fit results superimposed for the events in the $M_{\rm bc}$ ($\Delta E$) signal region. The solid curves represent the fit results, while the solid (dashed) peaks represent the signal ($K^+\ell^+\ell^-$ background) component.

TABLE I: A summary of the signal yields ($N_s$), reconstruction efficiencies ($\epsilon$), statistical significance ($\Sigma$), branching fractions ($\mathcal{B}$), and the corresponding upper limits (U.L.) at the 90% confidence level. The errors associated with branching fractions are sequentially statistical errors, systematic errors proportional to the branching fractions (given in Table II), and additive systematic errors related to yield extraction.

| Mode | $N_s$ | $\epsilon$ (%) | $\Sigma$ | $\mathcal{B}$ ($10^{-8}$) | U.L. ($10^{-8}$) |
|---|---|---|---|---|---|
| $B^+ \to \pi^+\mu^+\mu^-$ | $0.5^{+2.8}_{-1.9}$ | 13.1 | $0.2\sigma$ | $0.6^{+3.2}_{-2.2}\pm0.0\pm0.7$ | 6.9 |
| $B^+ \to \pi^+e^+e^-$ | $1.4^{+3.2}_{-2.3}$ | 13.8 | $0.6\sigma$ | $1.5^{+3.5}_{-2.5}\pm0.1\pm0.8$ | 8.0 |
| $B^+ \to \pi^+\ell^+\ell^-$ | - | - | $0.6\sigma$ | $1.0^{+2.3}_{-1.8}\pm0.1\pm0.4$ | 4.9 |
| $B^0 \to \pi^0\mu^+\mu^-$ | $5.1^{+4.2}_{-3.3}$ | 9.6 | $1.8\sigma$ | $8.1^{+6.7}_{-5.2}\pm0.8\pm1.0$ | 18.4 |
| $B^0 \to \pi^0e^+e^-$ | $2.7^{+5.2}_{-4.0}$ | 7.4 | $0.7\sigma$ | $5.5^{+10.7}_{-8.3}\pm0.5\pm2.0$ | 22.7 |
| $B^0 \to \pi^0\ell^+\ell^-$ | - | - | $2.0\sigma$ | $7.4^{+5.4}_{-4.5}\pm0.7\pm0.8$ | 15.4 |
| $B \to \pi\ell^+\ell^-$ | - | - | $1.2\sigma$ | $2.4^{+2.5}_{-2.1}\pm0.2\pm0.2$ | 6.2 |

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TABLE II: Summary of the contributions of systematic uncertainty proportional to the branching fractions (in %).

| Decay | $B^+ \to \pi^+\mu^+\mu^-$ | $B^+ \to \pi^+e^+e^-$ | $B^0 \to \pi^0\mu^+\mu^-$ | $B^0 \to \pi^0e^+e^-$ |
|---|---|---|---|---|
| Tracking efficiency | 3.0 | 3.0 | 2.0 | 2.0 |
| $e/\mu$-identification | 5.5 | 4.4 | 5.5 | 4.4 |
| $\pi^+$-id./$\pi^0$ reconstruction | 1.0 | 1.0 | 4.0 | 4.0 |
| Background suppression | 1.8 | 1.8 | 1.8 | 2.4 |
| PDF Modeling | 2.2 | 2.2 | 5.3 | 5.3 |
| MC decay model | 3.8 | 2.6 | 3.8 | 2.6 |
| MC statistics | 0.8 | 0.8 | 1.1 | 1.1 |
| $N(B\overline{B})$ pairs | 1.3 | 1.3 | 1.3 | 1.3 |
| Total | 8.1 | 6.8 | 10.0 | 9.1 |

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